Analysis and Modal Survey Test of Intelsat VIIA Deployed Solar Array

K. C. Jiang and R. Gahart

Space Systems/Loral

Palo Alto, Ca.

Abstract

A nonlinear normal modes analysis and a modal survey test have been performed to determine the frequencies and mode shapes of a large flexible deployed solar array for the Intelsat VIIA series communication satellites under production at Space Systems/Loral. Test parameters such as gravity, air mass and test fixture stiffness are included in the analysis. MSC/NASTRAN Solution 105 was used to generate the gravitational stiffness due to 1-g gravity and Solution 103 was used to calculate the frequencies. A DMAP Alter was updated for MSC/NASTRAN Version 67 to combine the Solution 105 gravitational stiffness matrix and Solution 103 structural stiffness matrix. The modal survey test was performed to measure frequencies and mode shapes for correlation with the analytical results. The deployed solar array was hung vertically. The solar array was pulled and released suddenly to excite transient vibrations. The decaying vibration response was measured and analyzed to deduce the frequencies. The test results show good correlation with the predictions.

1. Introduction

The Intelsat VIIA (I-VIIA) communication satellite is being designed and manufactured by Space System/Loral at Palo Alto, California under contract to International Telecommunication Satellite Organization (Intelsat). The deployed configuration of the I-VIIA satellite is shown in Figure 1. The two large four-panel solar array wings of the I-VIIA satellite induce low deployed frequencies for the fundamental modes of bending and torsion. These modes will be excited by the attitude control motions of the on-orbit satellite. The attitude control system is designed to avoid excessive excitation of these low frequency modes. The math model for control system design and analysis is derived from the finite element model used for structural analysis. Accurate prediction and measurement of the deployed frequencies of the I-VIIA satellite solar array is essential to proper attitude control performance.

The methodology to combine MSC/NASTRAN geometrical nonlinear analysis and normal modes analysis to predict the deployed solar array frequencies has been used by structural analysts (References 1 and 2). In May 1978, a three-panel deployed solar array of Intelsat V (I-V) satellite was analyzed and tested (References 3 and 4) by Space System/Loral (then named Ford Aerospace and Communications Corporation, FACC). The analysis was performed by using the in-house finite element code SAMIS to generate the structural stiffness matrix and mass matrix and to calculate the on-orbit deployed solar array frequencies and mode shapes. The Fortran program GENER was written to generate the gravitational stiffness matrix and added to the structural stiffness matrix to predict the deployed solar array frequencies under 1-g gravity. Air mass and test fixture stiffness were not considered in the analysis. The deployed solar array was hung vertically in a large vacuum chamber because the solar array is not strong enough to support itself when deployed horizontally in a 1-g field. The modal survey test was performed with air and without air in the chamber. The predicted frequencies for out-of-plane bending and in-plane bending were greater than the measurements by 8.5 and 36 percent, respectively. The predicted torsional frequency was 14 percent less than the measurement. The discrepancies of the in-plane bending frequency and torsional frequency between the analytical data and test data may have been caused by the test fixture stiffness, or inaccurately simulated test hardware stiffness and mass characteristics (Reference 4).

The Intelsat VIIA satellite deployed four-panel solar array wing is approximately 80 percent longer and 50 percent wider than the deployed Intelsat V three-panel solar array wing. The I-VIIA satellite deployed solar array can no longer fit into the existing vacuum chamber. The modal survey test must be performed under 1-g gravity and in the air. A dedicated test fixture was built to hang the deployed solar array vertically as shown in Figure 2. The measured frequencies have to be corrected analytically for the effects of gravity, air mass and the test fixture stiffness. MSC/NASTRAN Version 67 Solution 105 and Solution 103 were used to predict the on-orbit and on-earth deployed solar array frequencies and modeshapes. For the on-earth deployed frequency prediction, a MSC/NASTRAN DMAP Alter was updated to add the gravitational stiffness matrix to the structural stiffness matrix. The air mass was calculated and incorporated into the mass matrix. Test fixture stiffness was also measured for the frequency prediction.

2. Frequency and Modeshape Prediction

The finite element model of I-VIIA deployed solar array was developed using MSC/NASTRAN (Reference 5). The equation of motion to calculate the natural frequencies and modeshapes can be written as

$$([M]s + [M]air) \{ACCE\} + ([K]s + [K]grav) \{DISP\} = \{0\} \qquad (1)$$

where [M]s, [M]air, [K]s and [K]grav are the structural mass, air mass, structural stiffness and gravitational stiffness, respectively. Only the deployed solar array mass and stiffness are included in the on-orbit frequency prediction. To simulate the modal survey test, the air mass and the gravitational stiffness are considered in the analysis. The air mass was derived from the added mass equations described in Reference 6. The gravitational stiffness was generated by using MSC/NASTRAN Version 67 Solution 105 and added to the Solution 103 structural stiffness through a DMAP Alter given in Table 1. The predicted frequencies and modeshapes for on-orbit solar array and modal survey test configuration are given in Table 2 and Figure 3. Analysis results indicate that adding air mass reduces the frequencies of the out-of-plane bending modes and torsional modes by 26 percent and 12 percent, respectively. The in-plane bending mode, which moves very little air, has insignificant frequency reduction. The 1-g gravity load induces additional stiffness to the vertically hung solar array and significantly increases the values of the frequencies for all the modes.

3. Modal Survey Test

The modal survey test was performed on the I-VIIA deployed solar array wing in March 1992 at the Space System/Loral Environmental Test Laboratory. The test setup was under air mass and 1-g gravity load conditions.

A dedicated test fixture was built to support the deployed solar array vertically as shown in Figure 2. The solar array was instrumented with two out-of-plane and one in-plane low-g accelerometers. The accelerometer locations are at the lower end of the solar array as shown in Figure 4. Several strings were attached to the solar array at different locations. These strings were used to pull the solar array away from its static position and suddenly released to excite the fundamental modes or the higher modes as shown in Figure 5. Software was written to convert the decaying vibration response of the accelerometers from the time history domain to the frequency domain to determine the frequency. Figure 6 gives the typical time history and frequency response plots for an accelerometer. The frequencies and mode shapes results of the modal survey test are given in Table 2.

4. Conclusions

MSC/NASTRAN Solution 105 and Solution 103 were used to predict the frequencies and mode shapes for the Intelsat VIIA deployed solar array wing under 1-g gravity and air mass. The results presented in Table 2 showed that the predictions have very good correlation with the modal survey test data. All the predicted fundamental bending and torsional modes are within 8 percent of the test results. The updated MSC/NASTRAN Version 67 DMAP Alter to link the geometrical nonlinear analysis (Solution 105) and normal modes analysis (Solution 103) provides the same features as MSC/NASTRAN Version 67 Solution 106 nonlinear normal modes analysis (Reference 7). The modal survey test of the large flexible deployed solar array wing could be performed under 1-g gravity because of the nonlinear normal modes analysis capability to predict the frequencies and mode shapes. Avoiding modal survey testing under zero-gravity condition in a vacuum chamber reduces the project cost and prevents schedule delay. Furthermore, instead of using the simplified air mass calculation (Reference 6), the air mass can be treated as structural elements in the deployed solar array model (Reference 8).

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References:

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Table 1. DMAP Alter to Add Gravitational Stiffness to Structural Stiffness for MSC/NASTRAN Version 67 Sol 103

```
$***** ALTER TO ADD GRAVITATIONAL STIFFNESS MATRIX
$       TO STRUCTURAL STIFFNESS MATRIX
$
$*****  FOR MSC/NASTRAN V67 - SOL 103
$
COMPILE SEKR,SOUIN=MSCSOU,NOREF,NOLIST $
$
ALTER 20
TYPE DB,KDGG $
$***** INPUT GRAVITATIONAL STIFFNESS MATRIX GENERATED
$        BY SOL 105
DBVIEW KDGGQ=KDGG (WHERE SEID=SEID AND PEID=PEID AND,
    PROJECT='DIFF STIFFNESS' AND WILDCARD=TRUE) $
PARAML KDGGQ//'PRESENCE'////S,N,NOKDGGQ $
MESSAGE //' NOKDGGQ ='/NOKDGGQ $$
$***** ADD GRAVITATIONAL STIFFNESS MATRIX TO
$        STRUCTURAL STIFFNESS MATRIX
IF (NOKDGGQ <> -1) THEN $
  EQUIVX KDGGQ/KDGG/ALWAYS $
  MESSAGE //' KDGG + KGG FOR SEID'/SEID
  ADD KGG,KDGG/KGGPERS/ $
  EQUIVX KGGPERS/KGG/ALWAYS $
ELSE IF (NOKDGGQ = -1) THEN
   MESSAGE //'NO KDGG FOR SEID'/SEID $
ENDIF $
```

Table 2. Summary of Analysis and Test Results for the Frequency and Mode shape of Deployed Solar Array

Frequency (Hz)					test & prediction diff. (%)	Mode shape
Prediction				Test		
w/o air mass & w/o gravity	air mass only	gravity only	air mass & gravity	air mass & gravity		
0.0838	0.0622	0.188	0.139	0.151	7.9	1st op bending
0.528	0.392	0.659	0.483	0.503	4.0	2nd op bending
0.523	0.523	0.541	0.541	0.550	1.6	1st ip bending
1.002	0.882	1.031	0.907	0.883	-2.7	1st torsion
3.048	2.683	3.098	2.724	2.773	1.8	2nd torsion

op : out-of-plane; ip : in-plane

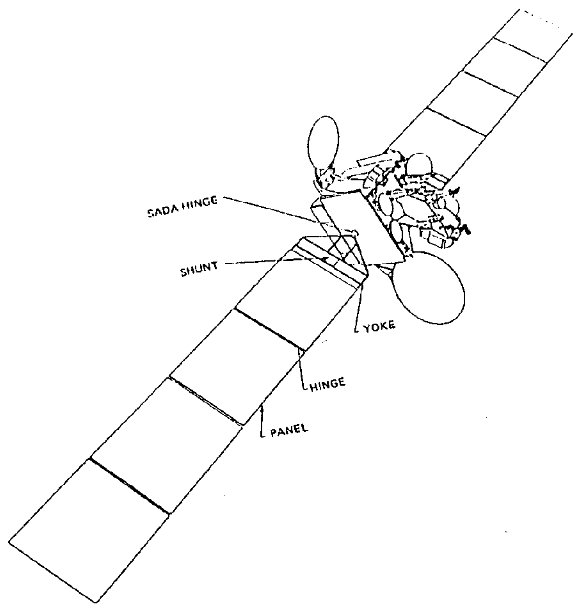

Figure 1. Deployed Intelsat VIIA Satellite Configuration

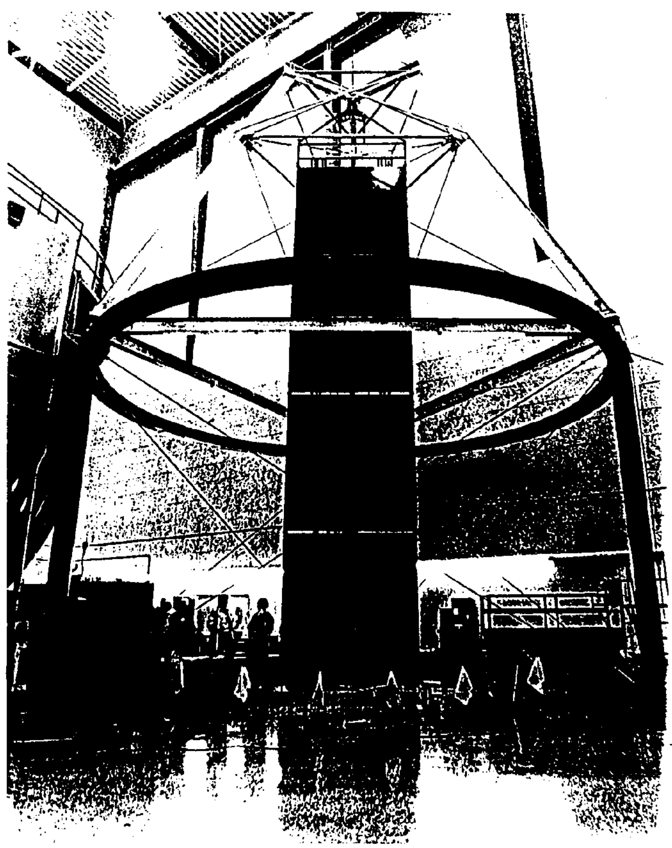

Figure 2. Test Fixture and Deployed Solar Array

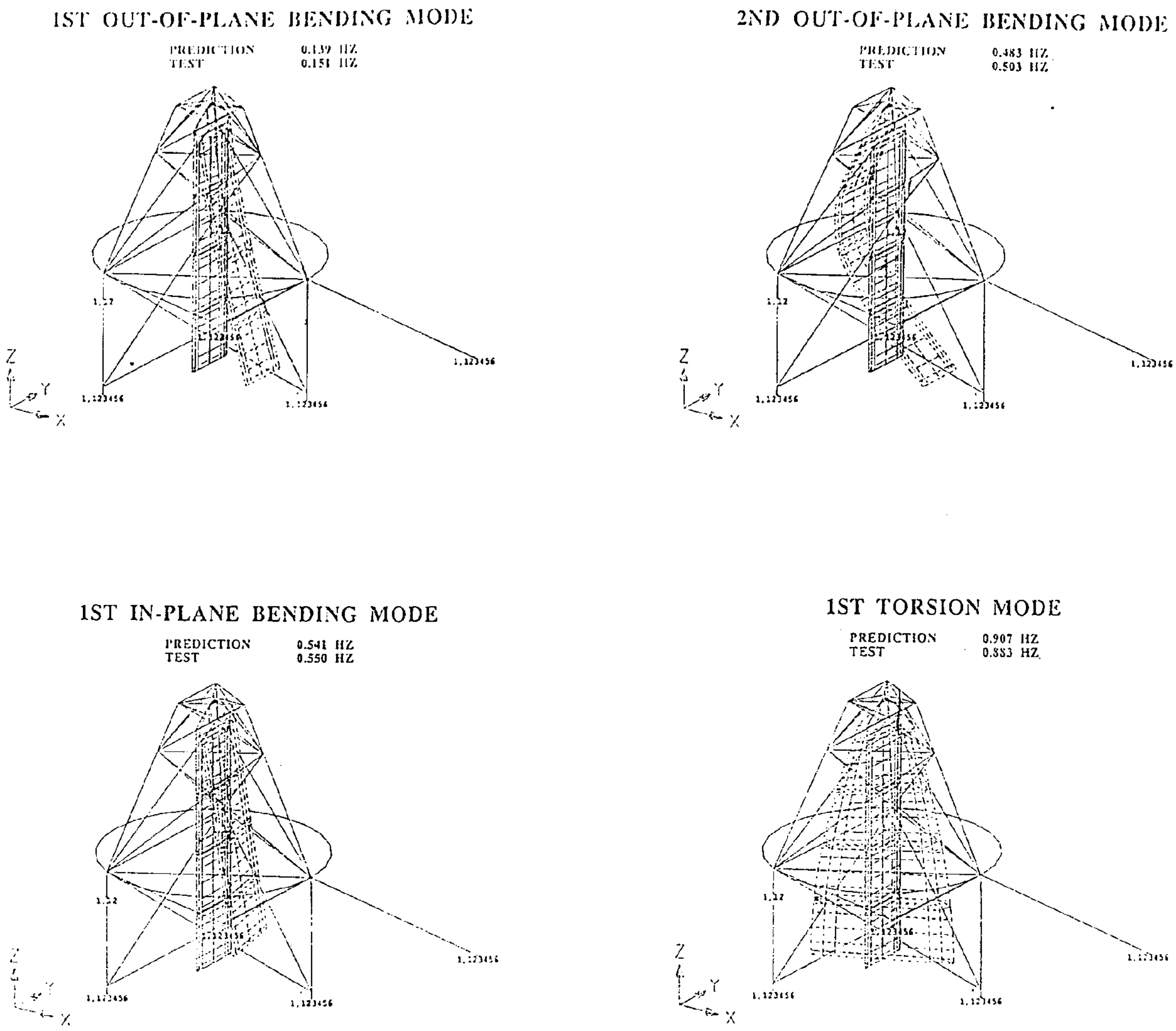

Figure 3. Frequency and Modeshape of Deployed Solar Array

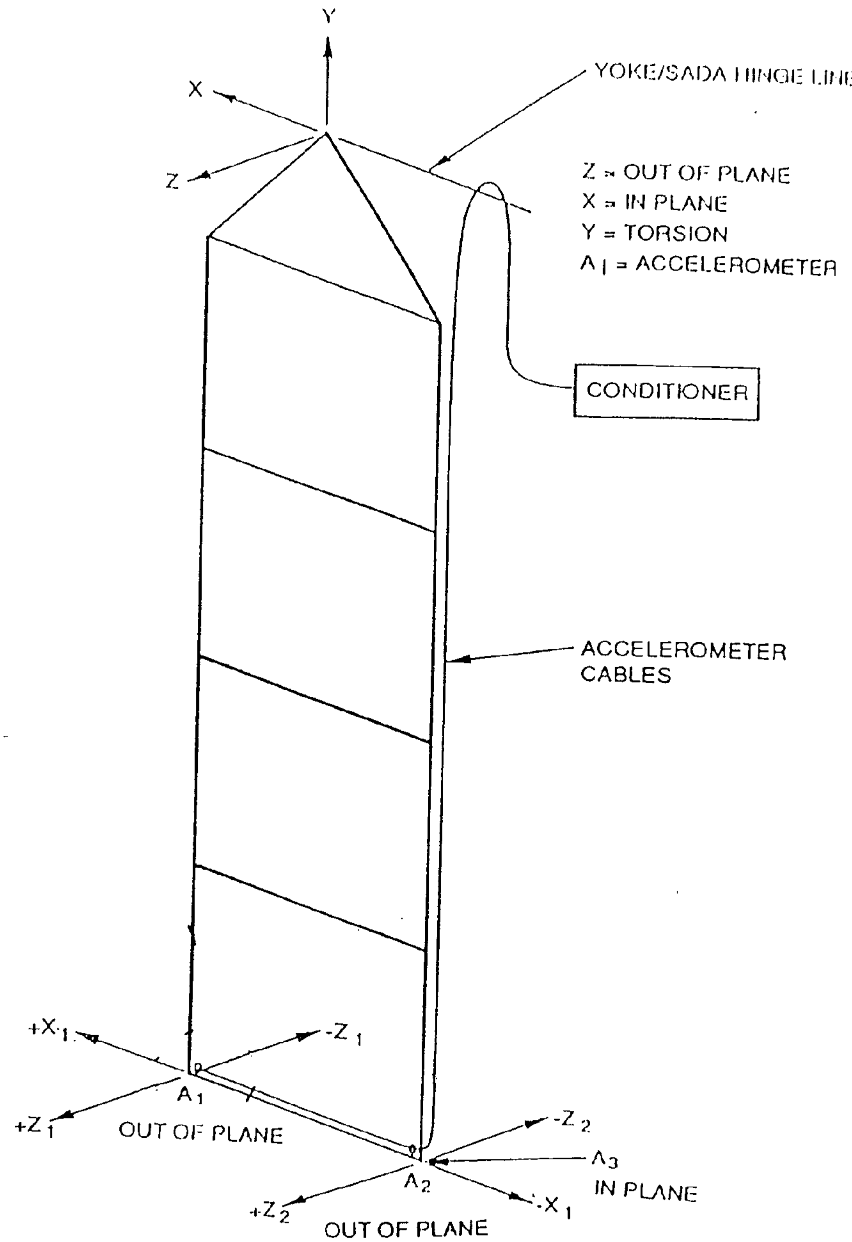

Figure 4. Accelerometer Locations

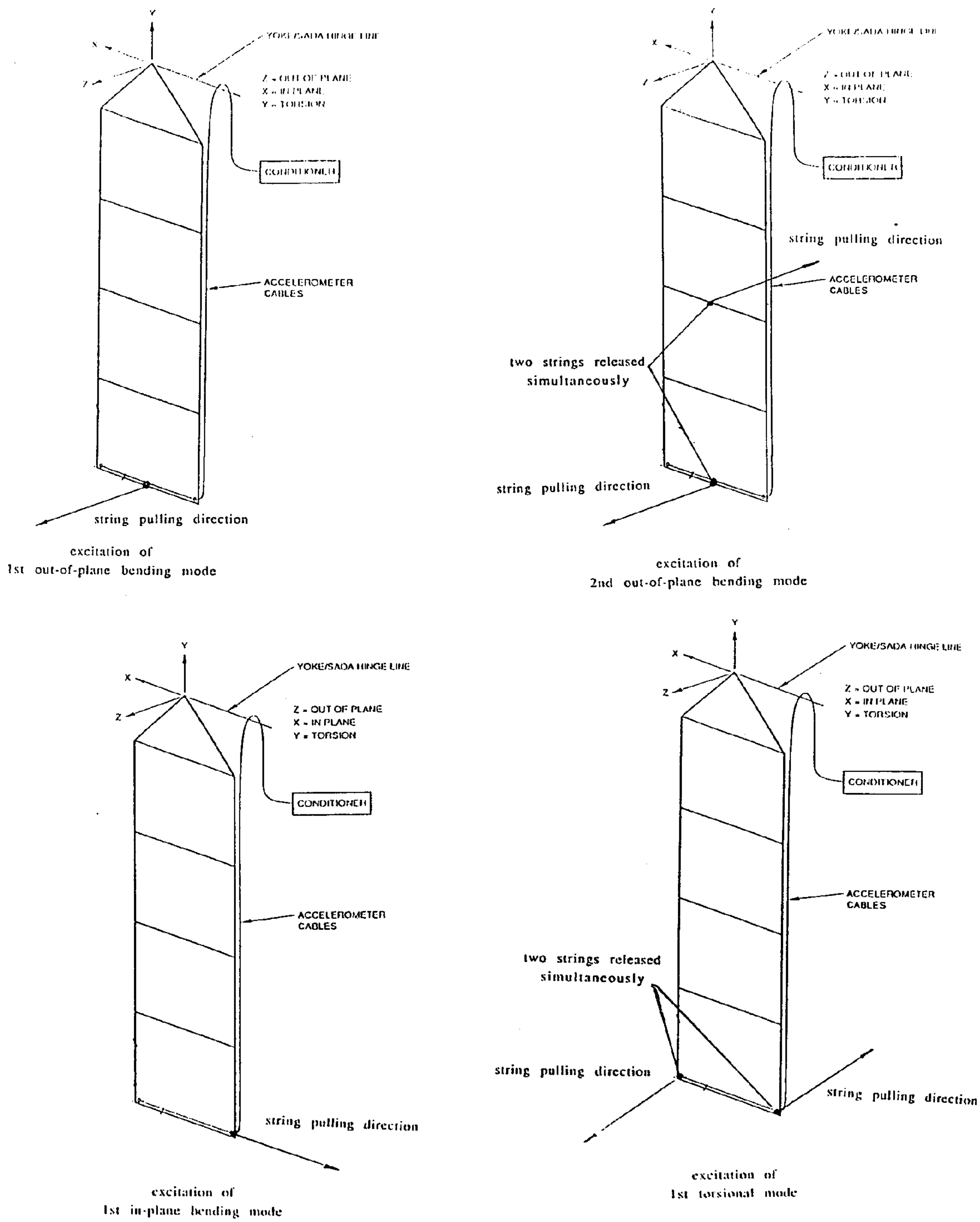

Figure 5. String Locations and Excitation of Modes

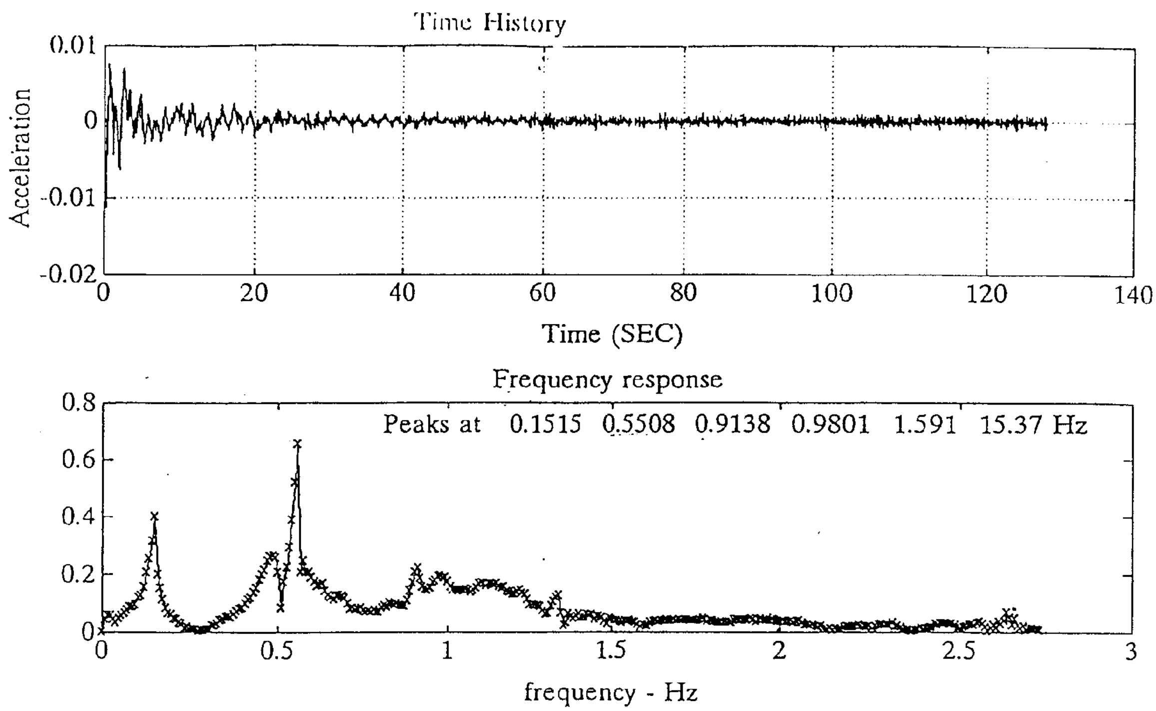

Figure 6. Typical Time History and Frequency Response Plots